DESIGN ON SWITCHING SEQUENCE FOR CONTROL CIRCUIT BY USING ALTERA MAX PLUS II

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DESIGN ON SWITCHING SEQUENCE FOR CONTROL CIRCUIT BY USING ALTERA MAX+PLUS II

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A project report submitted in partial fulfillment of the requirements for the award of Master of Electrical Engineering

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NOVEMBER 2007

I declare that this report on "Design on Switching Sequence for Control Circuit By Using Altera Max+Plus II" is the result of my own research except for works which have been cited in the references. The report has not been accepted any degree and not concurrently submitted in candidature of any other degree.

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For my dearest husband Shahrizal,

My lovely daughter Balqish & my family for their encouragement and blessing

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In the name of Allah, the most Gracious and most Compassionate

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ABSTRACT

The purpose of this research work is to design digital switching sequence for control circuit. A digital system comes with more benefit than analog which is programmable, faster, precise and flexible. These proposed digital switching sequences are application for single-phase and three-phase inverters. By controlling analog circuits digitally, system cost and power consumption can be drastically reduced. The switching sequences are designed using Altera Max+Plus II and downloaded to University Program (UP1) development board unit which consists of two types of Complex Programming Logic Devices (CPLD). In this research work, MAX7000 has been chosen to download the proposed switching sequence that has been designed. To prove the validity of the switching sequences chosen for single-phase and three-phase inverter, MATLAB/ Simulink is used as the simulation software. At the end of this research work, the digital switching sequences for single-phase and three-phase inverter have successfully been designed.

ABSTRAK

Tujuan kajian ini dijalankan adalah untuk menghasilkan jujukan suis bagi litar kawalan secara digital. Sistem digital adalah lebih baik berbanding dengan sistem analog. Ia boleh diprogramkan, lebih pantas, persis dan mudah diubah suai. Jujukan suis yang dihasilkan adalah untuk kegunaan penyongsang satu fasa dan penyongsang tiga fasa. Dengan mengawal litar analog secara digital, kos sistem dan penggunaan kuasa dapat dikurangkan secara mendadak. Jujukan suis dihasilkan menggunakan perisian Altera Max+Plus II dan diprogramkan ke dalam papan (UP1) *University Program*. Terdapat dua jenis CPLD (Complex Programming Logic Device) di dalam satu unit papan UP1. Dalam kajian ini, MAX7000 dipilih untuk memprogramkan jujukan suis yang telah dihasilkan. Bagi membuktikan kesahihan jujukan suisyang digunakan, simulasi dijalankan ke atas litar penyongsang satu fasa dan tiga fasa menggunakan perisian MATLAB/Simulink.. Pada akhir kajian ini, jujukan suis secara digital telah berjaya dihasilkan dan diprogramkan seperti yang dikehendaki. Dapatan kajian sedia digunakan sebagai pengawal digital jika di sambungkan dengan penyongsang sebenar.

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LIST OF SYMBOLS/ ABBREVIATIONS

Symbols:

Γ	-	Micro (10^6)
:	-	Ohm
f	-	Frequency (*Hz*)
Σ	-	Pi (180)
6	-	Sum
Z	-	Omega
M	-	Phase displacement
C	-	Capacitance
k	-	kilo (10^3)
L	-	Inductor
m	-	mili (10^{-3})
M	-	Mega (10^6)
T	-	Switching period

Abbreviations:

AC	-	Alternating Current
DC	-	Direct Current
THD	-	Total Harmonic Distortion
UPS	-	Uninterruptible Power Supply
CVCF	-	Constant Voltage and Constant Frequency
KV	-	Kilo-Volt
BJT	-	Bipolar Junction Transistor
TTL	-	Transistor-transistor Logic
MOS	-	Metal Oxide Semiconductor
CMOS	-	Complementary Metal Oxide Semiconductor
MCT	-	MOS-Controlled Thyristor
IGBT	-	Insulated Gate Bipolar Transistor
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
PWM	-	Pulse Width Modulation
ASIC	-	Application Specific Integreter
DSP	-	Digital Signal Processor
PAL	-	Programmable Array Logic
IEEE	-	Electrical and Electronic Engineer
GAL	-	General Array Logic
CPLD	-	Complex Programmable Gate Array
FPGA	-	Field Programmable Gate Array
VHDL	-	Very High Description Language
HVDC	-	High Voltage Direct Current
GTO	-	Gate Turn-Off
EDA	-	Electronic Design Automatic
SRAM	-	Static Random Access Memory

UP	-	University Program
LED	-	Light-emitting diode
ADC	-	Analog to Digital Converter
PID	-	Proportional Integral Derivative
RAM	-	Random Access Memory
RMS	-	Root mean square
U/D	-	Up / Down
VSI	-	Voltage Source Inverter
CSI	-	Current Source Inverter

CHAPTER 1

INTRODUCTION

1.1 Introduction to Power Electronic

Power electronic can be defined as the use of electronic devices to control and convert electric power. Power electronic is combined of power, electronics and control. It may be defined as the applications of solid-state electronics for the control and conversion of electric power. It is based on the switching of power semiconductor devices whose power handling capabilities and switching speeds have improved tremendously over the years. The switching characteristics of power devices permit the control and conversion of electric power from one to others. Versatile circuit topologies can be found in the power electronics for different applications [1].

1.1.1 History of Power Electronic Devices

Power Electronics began with the introduction of the mercury arc rectifier in 1900. This was followed by the first electronic revolution which began in 1984 with the invention of the silicon transistor.

The second electronic revolution began in 1958 with the development of thyristor. This caused the beginning of new era for power electronics, since many power semiconductor devices and power conversion techniques were introduced using thyristor. Next, was the microelectronics revolution which gave the ability to process a huge amount of data in a very short time. The power electronics revolution with merges power electronics and microelectronics provides the ability to control large amount of power in very efficient manner. Power electronics have already found an important place in modern technology and are now used in a great variety of high-power products, including motor controls, power supply and High Voltage Direct Current (HVDC) systems [1].

1.1.2 Definition of Power Electronics

Power electronics is defined as the application solid state electronics for the control and conversion of electronic power. Power electronic is based on the switching of power semiconductor devices whose power handling capabilities and switching speeds have improved tremendously over the years. It is presently playing an important role in modern technology and is used in variety of high power product for example; motor control, heat control, light control and power supply [2].

1.1.3 Significance of Power Electronics

The demands for control of electric power exist for many years. The generation, transmission and distribution of electric power are almost Alternating Current (AC) today. But, in industry, transportation, agriculture, and everyday life often demand Direct Current (DC) power. In any technically and economically defined situation, it is necessary to provide the most suitable form of energy to meet the demand of user [3]. Power electronics is the technology associated with the efficient conversion, control and conditioning of electric power by static means from its available input form into the desired electrical output form. The goal of power electronics is to control the flow of energy from an electrical source to an electrical load with high efficiency, high ability, high reliability, small size, light weight and low cost [4].

1.2 Power converter

Power electronics converters are a family of electrical circuits which convert electrical energy from one level of voltage, current or frequency to another level using semiconductor- based electronic switch. Versatile circuit topologies can be found in power electronics for difference applications [5].

The essential characteristic of these types of circuits is that switches are operated only in one of two states – either fully ON or fully OFF, unlike other types of electrical circuits where the control elements are operated in a linear or nearly linear active region.

As the power electronics industry developers, various families of power electronic converters have evolved, often linked by power level, switching devices, and of topological origins [5]. In terms of conversion form, it can be identified into four categories. They are AC to AC, AC to DC, DC to AC and DC to DC:

1.2.1 AC to AC Converter (cycloconverter)

AC to AC converter controls the rms values of AC voltage applied to the load. This converter converts an AC voltage, such as the main supply to another AC voltage. The amplitude and frequency of input voltage tend to be fixed values, whereas both the amplitude and frequency of output voltage tend to be variable without any intermediate conversion link. Single-phase and three-phase cycloconverter is the example of this type of converter. These cycloconverters have a high power output, of the order a few megawatts[1].

1.2.2 AC to DC Converter (Rectifier)

AC to DC converter or rectifier changes an alternating voltage to dc voltage. It can be classified as uncontrolled and controlled rectifiers. Uncontrolled rectifier circuits are built with diodes, and fully-controlled circuits are built with Silicon control rectifier (SCR), thyristors or power transistors. In AC to DC converter, line frequency diode rectifier that are increasingly being used to convert the line frequency AC input to a uncontrolled DC output voltage. Primary voltage of a switched mode power supply is an example of uncontrolled DC voltage supply [6].

In some application, it is necessary to control the DC voltage. In this case, average DC side voltage can be controlled from a positive maximum to negative maximum. Its use for battery charger and controlled motor drives use the controlled DC voltage [3].

1.2.3 DC to AC Converter (Inverter)

The converter that changes a DC voltage to an alternating voltage is called an inverter. Switch mode DC to AC converter, accepts the DC voltage as the input, and produces the desired AC voltage at the output, whose magnitude and frequency both can be controlled [1].

The power semiconductor devices such as BJTs, power MOSFETs, insulated gate bipolar transistors (IGBTs) and MOS-cotrolled thyristor (MCTs) are used nowadays. Currently, only the inverter with a high power rating, such as 500kW or higher, are likely to be built with either SCRs or gate turn-off thyristors (GTOs). There are many inverter circuits and techniques for controlling an inverter varies in complexity. AC motor drives control and uninterruptible AC power supply widely use this DC to AC converter [1].

1.2.4 DC to Dc Converter (Chopper)

DC to DC converter circuit is called a chopper. This converter coverts a DC supply to another magnitude DC supply. Switched mode DC to DC converters are use to convert the unregulated DC input to a controlled DC output at desired voltage level [6]. A SCR is rarely used in DC to DC converter. A power BJT or power MOSFET is normally used in such a converter and this converter is called a switch-mode power supply. The DC to DC converters are widely used in regulated switch-mode DC power supplies and DC motor drive application. Buck (step-down) converter, Boost (step-up) converter, Buck-Boost (step-down/step up) converter, Flyback converter, Forward converter, and Cuk converter are some example of DC to DC converter.

1.3 Problem statement

In power electronic applications, there are several types of circuit to convert power from one form to another. They are called converters and categorized into four types: rectifier (ac/dc), dc converters (dc/dc), ac converters (ac/ac) and inverter (dc/ac). In this dissertation, the research topic is inverters. Inverters are widely used for dc to ac power conversion with a variable voltage and variable frequency. Some of the applications of inverters are the speed control of ac machines, dc power transmission lines and renewable energy applications. Nowadays inverters use high power switching transistors either IGBT or MOSFET. In addition, the voltage and frequency of the source can be adjustable.

AC motor speed control applications require constant volt-frequency ratio. The ratio needs to be kept constant in case of saturation. In this case, inverters are used for this control scheme. From a dc voltage or current source, the inverter can provide output voltages with desired frequency and magnitude. Another inverter application is in dc transmission line. To transfer power from one point to another, ac or dc transmission lines are used. For cost saving reasons, dc transmission lines are preferred for longer distances, although ac electrical network is widely used in generation, transmission and distribution level. At both end of the dc transmission line, converters are needed for the power conversion.

Next, the other common applications of inverters are in renewable energy powered systems. In spite of high initial cost, long-term return benefit and some application areas make the used of these systems to be attractive. One of the renewable energy sources is photovoltaic systems. The energy from sunlight is converted to the electrical energy. The solar units provide dc voltage. So, to use the energy in ac application such as refrigerator and air conditioning units need an inverter.

All of the information above proved that inverters are used widely in the industry. Basic concerns in the design of inverters are cost, waveform quality, loss and controllability.

There are two systems to process signals. One is analog system and the other is digital system. Generally, a digital system comes with more benefits compared to analogue system. It is programmable, faster, precise, and flexible. Besides, as the signals are discrete but not continuous, a digital system can be less affected by the changes of elements' nature such as the problem of worn-out transistors. Those are the reasons why digital systems are greatly adopted in the world.

With the advances of programmable logic devices (PLD), field programmable gate array (FPGA) and Complex Programmable Logic Device (CPLD) provide a low-cost solution in implementing very complex digital circuit. The development of PLD technology also initiates its applications in digital motor and motion control. The CPLD is a new branch of the PLD family with very high gate counts; this makes it possible to implement complex control algorithm. For recent years, (CPLD) is increasingly developing very fast and has the advantages of high speed, large scale and easy-to design software. It is convenient to use CPLD to design the circuit, simulate and verify the result, and it is also easy to debug the hardware using ISP (In System Programmable). So, this algorithm is easily realized. If it is necessary to adopt the improved algorithm, only have to modify the algorithm in the software, then download file to chip using ISP; it has nothing to do with the hardware circuit.

Therefore, the interest of this research work presented in this report is to design the switching sequence for control circuit applications for single-phase and three-phase inverter. Altera Max+Plus II has been chosen as the software aided to design the switching sequence that used to control power switches of inverter digitally.

1.4 Aim of the study

The aim of this study is to design the switching sequence applications for single-phase and three-phase inverter by using Altera Max+Plus II software and download into University Program (UP1) development board unit .

1.5 Objectives of the study

Below are the objectives of this research:

1. To create and simulate three-phase inverter circuit by using MATLAB/Simulink and study the power switching concept of the inverter.
2. To design switching sequence for three-phase inverter by using ALTERA Max+Plus II development tool with University Program (UP1) board.
3. To build a gate driver circuit by using IC HCPL3120 as optocoupler IC.

1.6 Research Scopes

In this project, two types of software will be used for circuit simulation. First, the proposed three-phase inverter circuit will be simulated by using MATLAB/Simulink. The pulse switching sequence with 120° firing angle will be derived and simulated to control the signals on gate devices. The circuit will be tested and simulated with resistive load. Next, the main purpose of this project is to design and develop a digital controller for single phase and three-phase inverter switching sequence with 120° firing angle by using CPLD Altera Max+Plus II development tools and then download into UP1 board unit. Then, a gate driver circuit will be built by using IC HCPL3120 as optocoupler IC for amplified the voltage signal from the CPLD.

1.7 Report Outline

This report aims to outline the research work pertaining to the implementation in designing the switching sequence application for inverter by using Altera Max+Plus II.

Chapter 2 discusses about theory of single-phase and three-phase inverter. Besides, the digital control b using CPLD is also explained in this chapter. Hence, the review of important research works related to this study is then presented.

In Chapter 3, the methodology for the whole project is described in detail. It is started by simulation on single-phase and three-phase inverter by using MATLAB/ Simulink software. Then, the switching sequence is designed by using Altera Max+Plus II. It is followed by downloading the proposed switching sequence to University Program (UP1) board and gate driver implementation to amplify the signal, so that the proposed switching sequence can be used as a digital controller for the inverter power switches.

Then, Chapter 4 presents and discusses the results of simulation and experimental and these results are compared with theoretical to provide an independent check on the validity of the switching sequence designed.

Finally, overall research work and its findings are summarized in Chapter 5. Besides, some suggestions for the future development of this project are presented.

CHAPTER 2

LITERATURE REVIEW

In high performance ac servo drives and uninterrupted power system, voltage/ current control is an essential part of the overall system. Over the past two decades, a lot of current control schemes have been developed in the literature [7]. Current control of inverter using analog technology takes advantages of fast dynamic response and mature design experience, but suffers disadvantages of complex circuitry, limited function, and less circuit flexibility.

With the advance of microprocessor technology, single chip microprocessor and digital signal processor (DSP) have been widely adopted to realize sophisticated current control algorithm. This control scheme takes advantages of simple hardware design and extensive software flexibility; however the control algorithm may be limited by available execution time. More complex control algorithm may need a multiprocessor solution [8].

Owing the rapid development in semiconductor manufacturing technology, the function and algorithm specific IC (FASIC) becomes a good solution for high-speed applications. There are two major approaches in the development of and FASIC; design it as a specific microcontroller or a programmable peripheral. In the microcontroller approach, it need to develop special processor architecture that is convenient to perform specific functions and processes special instruction sets to improve computation performance.

This approach can significantly reduce the chip size due to common usage of an instruction set. However, its incompatibility to other microprocessors needs a large investment in the development of software supporting tools. These obstacles can be removed by adopting the peripheral approach with a downside of larger chip size. Using the peripheral approach, the FASIC is operating as a co-processor with another microprocessor [9]. This approach can significantly simplify the system design and make a great improvement for specific control functions.

The FASIC provides a feasible solution for prototyping of complex digital system. However, the extensive develop time and high setup cost for prototyping make it not an economic solution for product development in its early stage. With the advances of programmable logic device (PLD), field programmable gate array (FPGA) [10] and complex programmable logic device (CPLD) [11] provide a low cost solution in implementing very complex digital circuit. The development of PLD technology also initiates its applications in digital motor and motion control. In this research work, CPLD is used in designing switching sequence to control the power switches application for inverter.

2.1 Basic Theory of Inverters:

Power inverters can be broadly classified as either the voltage-source inverter (VSI) or current-source inverter (CSI) type. For a VSI, the inverter is fed from a dc voltage source usually with a relatively large capacitor connected in parallel. It is well known that the maximum ac voltage output of a VSI is limited to 1.15 times half the dc source voltage (using modulation strategies with triplen offsets added) before being over-modulated. On the other hand, a CSI is fed from a dc current source, which is usually implemented by connecting a dc source in series with a relatively large inductor, and its ac voltage output is always greater than dc source voltage that feeds the dc-side inductor.

2.1.1 Voltage Source Inverter

A voltage source inverter (VSI) is the most commonly used type of inverter. In a VSI the input DC voltage source is essentially constant and independent of the load current drawn. The input DC voltage may be from an independent source such as a battery or may be the output of a controlled rectifier. A large capacitor is placed across the DC input line to the inverter. The capacitor ensures that any switching events within the inverter do not significantly change the DC input voltage. The capacitor charges and discharges as necessary to provide a stable output. The inverter converts the input DC voltage into a square-wave AC output source.

2.1.1.1 Half Bridge VSI

The half-bridge inverter, which is used for low-power applications, is the basic building block of inverter circuits. Figure 2.1 shows a single-phase half-bridge VSI configuration that uses two switches (S1 and S2) and two DC power supplies. The switching device can be a power transistor (a BJT or a MOSFET) a GTO thyristor, or an SCR with its commutation circuit. Diodes D1 and D2 are freewheeling diodes.

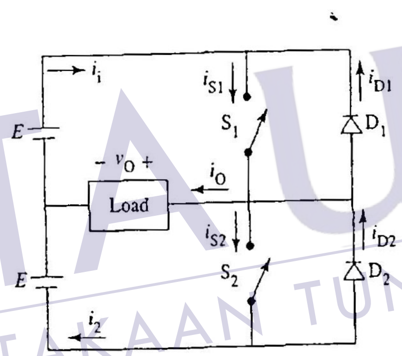

Figure 2.1: Half-Bridge VSI

Figure 2.2 shows the output voltage waveform with resistive load. The switches are turned on and off alternately, with one switch on while the other off. During the period 0 to T/2, switch S1 is closed which makes vo= +E. At T/2 , S1 is opened and S2 is closed. During the period T/2 to T, the output voltage v=-E. Therefore, the output voltage has an alternating rectangular waveform of frequency f=1/T. By controlling T, we can control the frequency of the inverter output voltage. However, care must be taken not to turn both switches on, as they will short circuit the dc source.

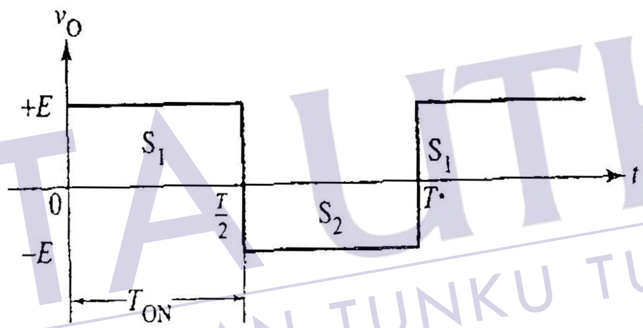

Figure 2.2: Output Voltage Waveform With Resistive Load

2.1.1.2 Full Bridge Voltage Source Inverter

A full bridge VSI can be constructed by combining two half-bridge VSIs. The basic principle for designing an inverter from a dc power supply, using a scheme is known as the bridge inverter illustrated in Figure 2.3. Current is provided to the load from a dc power supply via the switches, S1, S2, S3, and S4. The switches S1, S2, S3 and S4 are four semiconductor devices, such as transistor. Each switch has two states, ON or OFF. The state of the switches defines the voltage across the load. Table 1 shows their corresponding voltages.

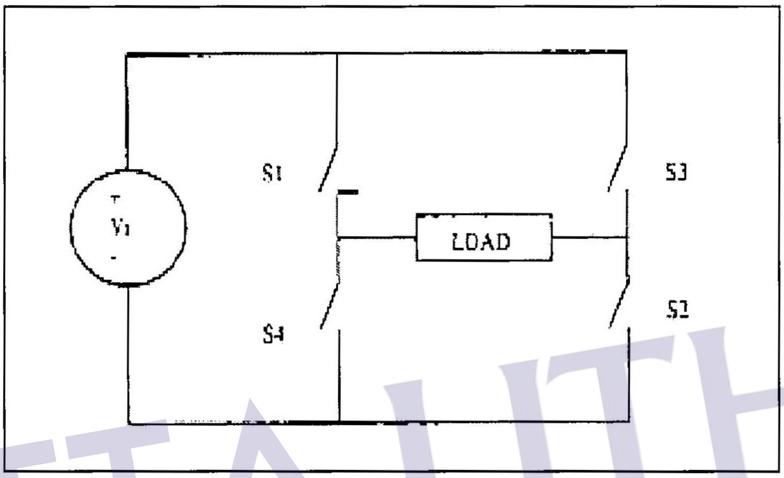

Figure 2.3: Full- Bridge Inverter

Table 2.1 : Corresponding Voltage with Four Switching States

State	S1	S2	S3	S4	Load Voltage
1	On	On	Off	Off	+Vi
2	On	On	On	On	0
3	Off	Off	On	On	-Vi
4	Off	Off	Off	Off	0

In state 1, S2 and S2 are closed and S3 and S4 are open. S1 and S2 connect the load to the dc power supply. In this state, the output voltage at the load terminal is Vi. In state 3, S3 and S4 are on and S1 and S2 are off. The output voltage becomes –Vi. When the states 1 and 3 are repeated alternately, a square-wave voltage will be created across the load, as shown in Figure 2.4.

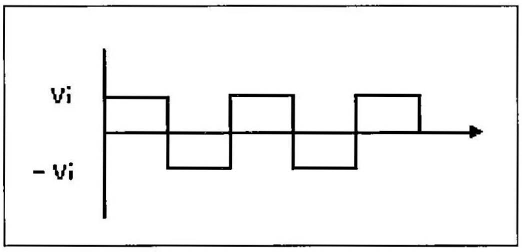

Figure 2.4: Square Wave Output Voltage

By comparing the waveforms of Figure 2.2 and 2.4 shows that the output voltage waveforms of the half-bridge and full-bridge inverter are identical. Therefore, the same equations apply. When the switching state is changed while going from one state to the other, both pair of switches must be in off state for a short time to avoid the possibility of short-circuiting the DC source in the transient state in which the two switches can be simultaneously closing. Therefore, switching from the on state to the off must be done as quickly as possible, while the switching from off to on must be carried out with an appropriate delay and take a definite time.

2.1.1.3 The Basic Principle of the Three-Phase Bridge VSI Inverter

AC motor drives typically require three-phase AC signals at the stator for their operation. The ability to control voltage and frequency of AC signals allows flexibility in improving the efficiency of AC motors.

A three-phase voltage source inverter as seen in Figure 2.5 consists of a power part and a control unit. The power part contains the semiconductor switching devices, which are used to complete a path between ac load and the dc power supply. Insulated Gate Bipolar Transistor (IGBT), Silicon Controlled Rectifier (SCR) and Field Effect Transistors (FET) are some of the semiconductor switching devices that can be used. The control unit provides the necessary pulses to turn the switches on and off in a sequence. The control unit assigns states to the switches such that the inverter generated the desired ac output.

Switches Sa, Sb, Sc, Sa', Sb' and Sc' are assumed to work ideally; i.e. when the switch is closed maximum current flows and there is zero voltage drop across the switch. Hence under ideal conditions there would be zero power loss in the switch. But practically switches have a small leakage current flowing through them in the Off state, and a small voltage drop in the On state. Moreover the transition from Off to On and vice-a-versa is not a perfect step function. Hence there would be losses during change of state (Switching losses). The diode across the switches are used to allow reverse inductive motor current to flow in the inverter, since switches (MOSFETs, IGBTs) allow current only in one direction. To prevent short-circuit; both the upper and lower switches are never torn On together. The turn On and turn Off times of switches are usually not identical and hence it is necessary to place a dead band between the turn On and Off period.

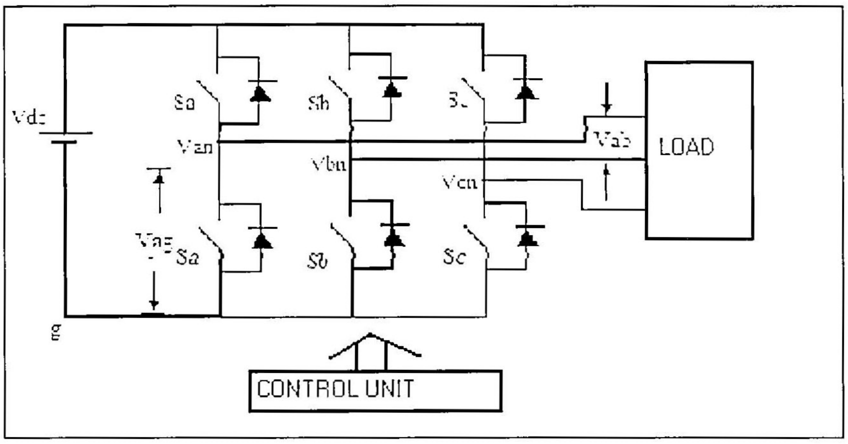

Figure 2.5: A Three-Phase Inverter

With the three upper switches there are $2^3=8$ possible switching states. These switching states are represented in Figure 2.6. For two switching states (000 and 111), the voltage produced across each of the phase is zero. Though these states produce "null voltage", they play an important role in increasing the linear modulation range as well as reduction in Total Harmonic Distortion (THD).

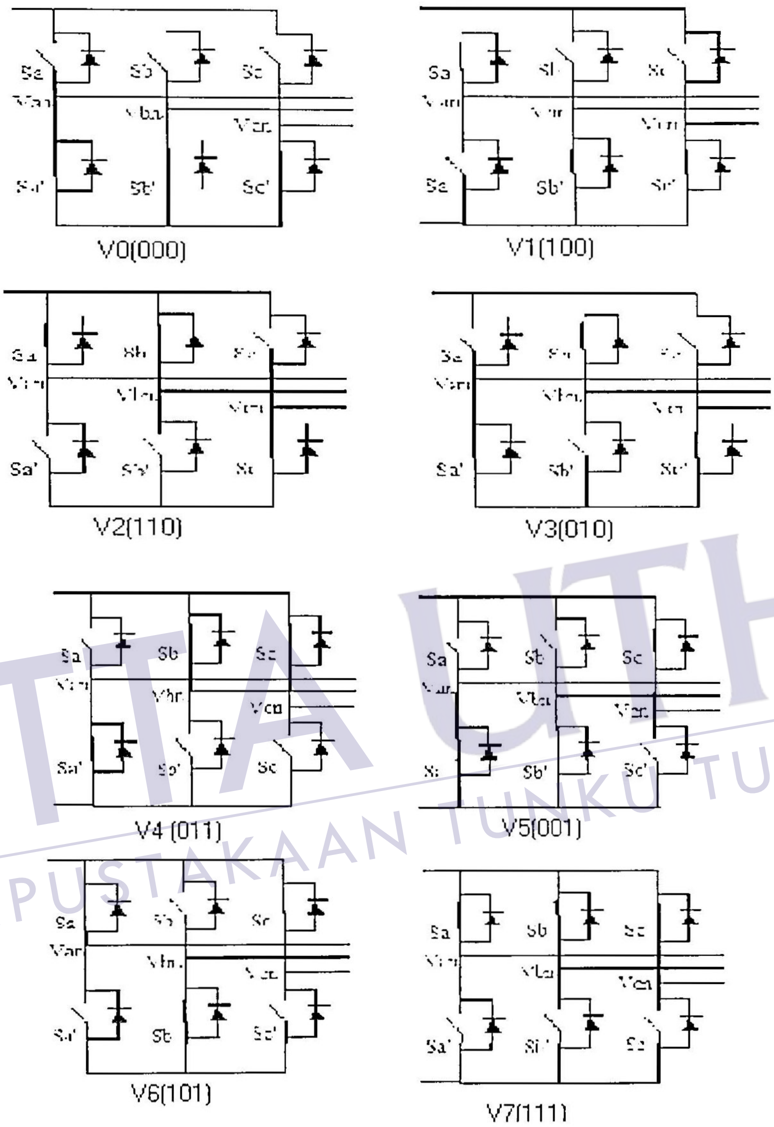

Figure 2.6: Switching States of a Three-Phase Inverter

Using a similar approach the line-neutral and line-line voltages can be calculated for the remaining switching sequences and is shown in table 2.2. From the table we notice that the line to line voltages varies between +Vdc and –Vdc. This is the maximum attainable voltage given a DC bus voltage of Vdc.

Table 2.2 : Switching Patterns in Three-Phase Inverter

Voltage V	Switching Pattern			Line to neutral voltages			Line to Line Voltages		
	Sa	Sb	Sc	Van	Vbn	Vcn	Vab	Vbc	Vca
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	(2/3)	(-1/3)	(-1/3)	1	0	-1
V2	1	1	0	(1/3)	(1/3)	(-2/3)	0	1	-1
V3	0	1	0	(-1/3)	(2/3)	(-1/3)	-1	1	0
V4	0	1	1	(-2/3)	(1/3)	(1/3)	-1	0	1
V5	0	0	1	(-1/3)	(-1/3)	(2/3)	0	-1	1
V6	1	0	1	(1/3)	(-2/3)	(1/3)	1	-1	0
V7	1	1	1	0	0	0	0	0	0

Each switch in the inverter bridge in Figure 2.5 can be fired to conduct for either 120° or 180°. As shown in Figure 2.6, each switch is gated for 120° conduction with resistive load. The load voltage (line value) has a stepped waveform and the current is quasi-square wave. For Figure 2.7, each switch is gated for 180° conduction. Three switches are conducting at any time. The line load voltage is quasi-square wave but the current waveforms are stepped.

2.1.1.4 The 120^{o} Conduction Type

The basic three-phase inverter can be controlled so that each switch conducts for a period of 120^{o}. In this situation, one two switches are conducting at any time, one from the positive group (S1, S3 and S5) and the other from the negative group (S2, S4 and S6). The two on switches connect two of the loads terminals to the DC supply terminals, while the third terminal remains floating. There are six intervals in one cycle of the AC voltage waveform. The switches are turn on at 60^{o} intervals of the output voltage waveform in the appropriate sequence to obtain line-to-line voltage. The rate of switching determines the output frequency.

To eliminate the possibility of shorting out the DC source must make sure that two switches in the same leg are not on simultaneously. Therefore, an interval of 60^{o} elapses between the end of conduction in switch S1 and the beginning of the conduction in switch S4, which is in the same leg as S1. The same is true for switches S3 and S6 and switches s5 and S2.

The phase voltage across the load VAN, VBN and VCN; can be determined for various 60^{o} durations with Y-connected resistive load. These voltages can be obtained by considering the equivalent circuits of the various inverter-load combinations for the six intervals. The results are summarized in Table 2.3.

Table 2.3: Switching Pattern for Six Intervals with 120°–firing angle

Inverter	S1	S2	S3	S4	S5	S6	Van	Vbn	Vcn
0-60 °	On	Off	Off	Off	Off	On	+E/2	-E/2	0
60°-120 °	On	On	Off	Off	Off	Off	+E/2	0	-E/2
120°-180°	Off	On	On	Off	Off	Off	0	+E/2	-E/2
180°-240°	Off	Off	On	On	Off	Off	-E/2	+E/2	0
240°-300°	Off	Off	Off	On	On	Off	-E/2	0	+E/2
300°-360°	Off	Off	Off	Off	On	On	0	-E/2	+E/2

Figure 2.7 shows the three line voltages. The step-wave line voltage waveforms are identical in shape but are displaced from each other by 120 °. Each switch is on for duration of 120 ° in sequence. When S1 is on at wt=0, terminal A is connected to the negative side of the DC source.

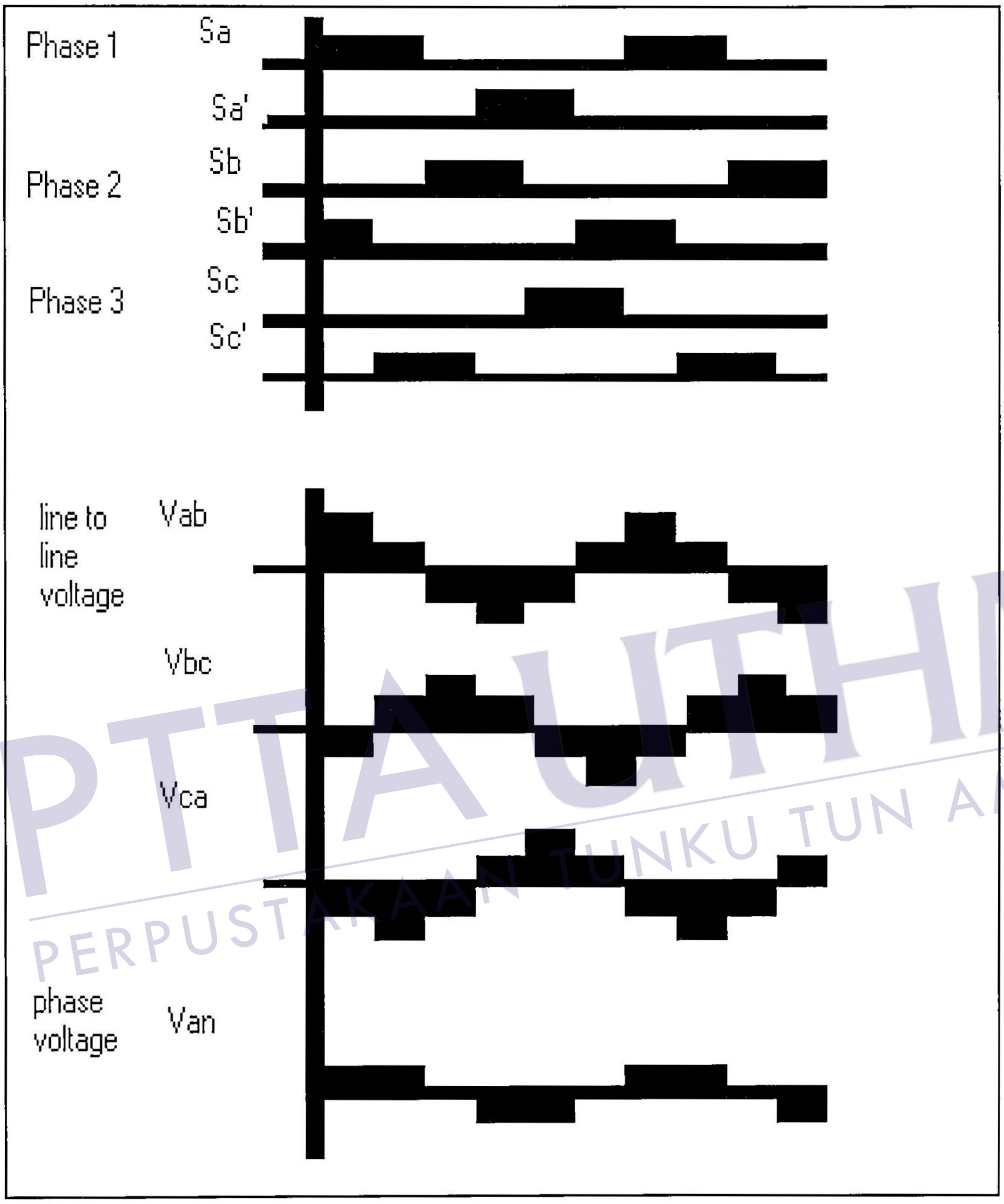

Figure2.7: 120° –firing with Y-connected R-Load.

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